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FINAL TECHNICAL REPORT

RESEARCH IN THE OPTICAL SCIENCES

Contract F49620-77-C-0138

August 1, 1977 through July 31, 1979

Submitted to
Air Force Office of Scientific Research
Bolling Air Force Base
Washington, D. C.

by

Optical Sciences Center
University of Arizona
Tucson, Arizona 85721
Peter A. Franken, Director

September 1979

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Molecular interactions	spectroscopy	Volumetric image display
Radiometry	Quantum optics	Electroreflectance spectra
Picosecond processes	Doped copper	Alkali halide windows

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This annual report under contract F49620-77-C-0138 covers work done from August 1, 1977 through July 31, 1979. Included are progress reports, publications, and papers submitted during that time period

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CONTENTS

INTRODUCTION

This final technical report to the Air Force Office of Scientific Research under contract F49620-77-C-0138 describes work accomplished from August 1, 1977 through July 31, 1979 by members of the Optical Sciences Center.

On the following pages we discuss the progress made under each task of the contract, the personnel supported by each task, and the manuscripts submitted for publication.

Manuscripts Submitted for Publication

H. Al-Abawi, F. A. Hopf, G. T. Moore, and M. O. Scully, "The quasi-Bloch equations and coherent transients in the free-electron laser," submitted for publication.

B. Bosacchi, "Picosecond spectroscopy and solid state physics," in Coherence in Spectroscopy and Modern Physics, F. T. Arecchi, R. Bonifacio, and M. O. Scully, eds. (Plenum Publishing, New York, 1978), pp. 305-327.

B. Bosacchi, C. Y. Leung, and M. O. Scully, "Ultrafast processes in the optical response of the electron-hole plasma in germanium," to be published.

J. J. Burke and J. B. Breckenridge, "Passive imaging through the turbulent atmosphere: fundamental limits on the spatial frequency resolution of a rotational shearing interferometer," J. Opt. Soc. Am. 68(1):67-77, January 1978.

T. Fu and M. Sargent III, "Effects of signal detuning on phase conjugation," SPIE Meeting, Albuquerque, New Mexico, May 1979.

R. S. Hershel, "Effects of partially coherent illumination on resist profiles in projection printing," Proceedings of Kodak Interface 78, San Diego, California, October 1978.

E. D. Huber, "An intercomparison of lens design computer programs--a new user's viewpoint," SPIE Meeting, San Diego, California, August 1978.

S. F. Jacobs, "How monochromatic is laser light?" Am. J. Phys. 47:597, 1979.

C. J. Kim, K. Shu, H. Oona, and S. O. Sari, "Properties of localized silicon dioxide clusters in layers of disordered silicon on silver," International Topical Conference on the Physics of SiO_2 and Its Interfaces, Yorktown Heights, New York, March 1978.

A. S. Marathay, "Generalized radiometry: discussion of two approaches," submitted for publication to the Journal of the Optical Society of America.

A. S. Marathay and W. Goring, "Directionality of light beams and spatial coherence," Physica Scripta 10:40, 1979.

M. Sargent III, "Standing-wave optical bistability and instability," submitted to Sov. J. Quantum Electronics.

S. O. Sari, "Remark on the thermal radiation from a resonant absorber," submitted for publication.

S. O. Sari, P. Hollingsworth Smith, and H. Oona, "Near infrared absorption in films of silicon containing oxygen," J. Phys. Chem. Solids 39:957-60, 1978.

P. W. Scott, "Image sampling and multiplexing two-dimensional phase gratings," SPIE Meeting, San Diego, California, August 1978.

M. O. Scully, "Coherent transient effects in Josephson junctions. I: formulation," submitted for publication.

M. O. Scully, "Suggestion and analysis for a new optical test of general relativity," submitted for publication.

S. A. Shakir, "Analytical properties of the initial value problem for zero area pulses," submitted for publication.

P. N. Slater, "Partial evaluation of a modified PDS microdensitometer," 31st Annual Conference of the Society of Photographic Scientists and Engineers, Washington, D.C., May 2, 1978.

O. N. Stavroudis and R. C. Fronczek, "Generalized ray tracing and the caustic surface," Optics and Laser Technology, August 1978, pp. 185-191.

A. F. Turner and S. D. Browning, "Refracting boundaries in thin film glass lightguides," 23rd SPIE International Technical Symposium, San Diego, California, August 1979.

Students Supported

In addition to the faculty listed in the individual task progress reports, the following students were supported by this contract:

W. Bomberger*
S. Browning
K. Castle
C. Ceccon
R. Chang
B. Comaskey*
B. Fritz
T. Fu
D. Goodman
C. Koliopoulos
G. Lawrence
T. Leung
M. Ruda
P. Scott
B. Seery
R. Scotti
S. Shakir
K. Shu
J. Shy
D. Sough
M. Sung
D. Thomas*
D. Tolliver*
T. Turner*
Y. Wang
D. Weinberger

*Qualified for Master of Science degree by passing Ph.D. preliminary examinations.

CATEGORY 1. OPTICAL DESIGN, FABRICATION AND TESTING

1-1. Analogs to Aspheric Optical Refracting Surfaces for Thin Film Waveguides--Dr. O. N. Stavroudis and Dr. A. F. Turner

1-2. Broadband Optical Switching with Ti-Diffused $LiNbO_3$ Waveguide Structures--Dr. J. J. Burke

1-3. Determination of Waveguide Modal Parameters and Attenuation Characteristics--Dr. J. J. Burke

1-4. Methods for Null Testing of Aspheric Surfaces--Prof. R. R. Shannon and M. C. Ruda

ANALOGS TO ASPHERIC OPTICAL REFRACTING

SURFACES FOR THIN FILM WAVEGUIDES

(O. N. Stavroudis and A. F. Turner)

Research Objective: To design, make, and test high-performance thin film waveguide lenses which are the counterparts of apsheric lenses in bulk optics. The program is a logical continuation of our phase of the present JSOP contract entitled "Precision Lens Elements for Integrated Optics."

Progress: In geometrical optics, Snell's law is the basic mathematical tool for lens design. A modified form of Snell's law has been shown to be applicable to the step-in-thickness type of construction of thin film lens components for optical waveguides. The modification consists of substituting mode indices for the bulk indices appearing in the conventional usage of Snell's law. In all of the contract work, however, a different construction is being used; namely high index overlay films on the interconnecting thin film waveguide. It is important to verify experimentally that the modified Snell's law also describes the refraction at the boundary between an overlay and a guide. This proves to be the case, as described in a paper prepared for the 23rd SPIE International Technical Symposium in San Diego, Aug. 27-30, 1979, entitled "Refracting Boundaries in Thin Film Glass Lightguides" by A. F. Turner and S. D. Browning.

A program is under way to evaluate some readily obtainable commercial glasses, such as Corning 0317, to replace microscope slides for waveguide substrates. The slides have become increasingly unsatisfactory because of poor surface quality.

Electron bombardment equipment for operation during film deposition has been installed in the 18-in. coater. It is expected to improve the loss characteristics of some of the evaporated films.

The first mask has been fabricated to produce an evaporated, thin film beam-expanding collimator lens.

A new electron gun was purchased for the box coater. It should eliminate the absorption troubles experienced in the evaporated glass waveguides and thought to be caused by stray electrons in the e-gun.

Four computer programs have been written for the numerical solution of a wide variety of problems encountered in multilayer waveguides. Another program was written for ray tracing through the aspheric thin film lenses under study.

Several designs for thin film beam-expanding collimator lenses with elliptical contours have been completed. The construction of appropriately shaped masks for their production by evaporative techniques is under way.

In the past two contract years, a firm base has been established for designing and then making, by vacuum evaporation methods, thin film refracting components for optical wavelengths.

BROADBAND OPTICAL SWITCHING WITH TI-DIFFUSED $LiNbO_3$ WAVEGUIDE STRUCTURES (J. J. Burke)

Research Objective: To develop low-drive-power, gigahertz bandwidth modulators and switches for CW optical sources with central wavelengths ranging from 0.6 to 1.3 μm. Our principal interest is in developing sources to test the dispersion properties of fiber optic cables over their full range of operating wavelengths.

Progress: Our theory of bending losses in single-mode, titanium-diffused channel waveguides in lithium niobate is now being evaluated numerically by Lynn Hutcheson (USNWC, China Lake). We will shortly be making direct comparisons with his experimental results. Lynn's work, though as yet unpublished, has caught the attention of others in his field, who have asked him to present it at the forthcoming Integrated Optics Meeting at Lake Tahoe. We are accordingly preparing two papers for this meeting, one on theory and one on the measurements. Preliminary comparisons indicate that the theory does indeed predict the experimental results. If further comparisons reinforce this conclusion, we will have made a significant contribution to this new field. There have been no definitive comparisons at optical frequencies in the past. This will be a first.

Ian White (Bell Laboratories, Norcross, Georgia) and James Burke (OSC) travelled to China Lake on June 28 and 29 to work with Lynn Hutcheson on the details of the theory: its derivation and interpretation. Burke also needed to review Hutcheson's experimental facilities and results, which are the substance of his dissertation. Hutcheson's work has been excellent. It will produce a first-class dissertation as well as several good papers. We shall be preparing these in the coming months.

DETERMINATION OF WAVEGUIDE MODAL PARAMETERS AND ATTENUATION CHARACTERISTICS (J. J. Burke)

Research Objective: (1) To provide a better theoretical basis for optimizing the refractive index profiles of fiber waveguides. (2) To develop the theory of bending loss in optical waveguides for the case of diffused guiding strips of $LiNbO_3$--now under experimental study at China Lake.

Progress: The previous months have been devoted to the theoretical investigation of interferometric techniques to measure the material dispersion in single mode fibers and to measure the intermodal delay of step index multimode fibers.

For the case of the multimode fiber, a mode group of the fiber can be associated with a given angular direction in the far field. Associated with each mode group is a characteristic modal phase. Hence, in the absence of material and waveguide dispersion, the curvature of the wavefront is a direct measure of the relative intermodal delays associated with the fiber.

We are awaiting delivery of various optical and mechanical components needed in the construction of a variable lateral shear interferometer. This interferometer is to be used in measuring the far field wavefront from the step index multimode fiber. The interferometer will be of the standard Michelson configuration with translatable cube corner reflectors to produce the lateral shear. Many of these components will also be used in the material dispersion measurements.

METHODS FOR NULL TESTING OF ASPHERIC SURFACES

(R. R. Shannon and M. C. Ruda)

Research Objective: To develop relatively simple tests to aid opticians in producing smooth, high quality sections of aspheric surfaces. Final acceptance of surfaces can also be made using the test approach.

Progress: The previous year has been devoted to the development of several testing methods: (1) The mathematical description of an aspheric section is complete to the 6th order. (2) A procedure has been developed for finding an initial starting design from which a good optical design program can arrive at a final solution. (3) Design, optimization, and analysis techniques for use with the design program ACCOS V have been developed. The tolerances on such items as lens tilt, decenter, and surface rotation were examined. The equations indicate that for the usual type of aspheric surface encountered, the tolerances are reasonable to the extent that no special equipment is needed to maintain the tolerances. (4) An alignment technique has been delineated that is straightforward to perform. A test facility capable of aligning rotationally symmetric systems will also be able to align this test arrangement.

As an exercise, a tilted null lens test was designed for a steep aspheric section. A 10-in. diameter section of a 30-in. diameter f/2.8 hyperbola with aspheric deformation coefficients was fabricated and tested some years ago at the Optical Sciences Center using more conventional techniques. The departure of the parent mirror from the paraxial sphere was 760 μm. In a preliminary comparison between the original null lens (designed to test the rotationally symmetric parent surface) and the newly designed tilted null lens (designed to test only the required section), the latter was found to be better. More specifically, it required fewer and slower lenses, no 60-in. diameter test sphere was needed, and the lenses were comparable in size. The new design appears to have looser tolerances than the old design and it should be more straightforward to align. Although it too requires a computer-generated hologram (CGH) to clean up the residual wavefront error, these errors have only one-third the optical path difference and one-eighteenth the slope errors of the original null lens.

In summary, the test design and procedure have been examined and documented. Under the proper circumstances the test can be regarded as a better alternative null test method to more conventional techniques.

CATEGORY 2. QUANTUM OPTICS AND RADIOMETRY

2-1. Theoretical Studies of the Free-Electron Laser--Dr. M. O. Scully

2-2. Molecular Interactions--Dr. R. L. Shoemaker

2-3. Radiometry of Partially Coherent Light--Dr. A. S. Marathay

2-4. Study of Picosecond Processes in Semiconductors--Dr. M. O. Scully

2-5. Proposed Experiment on Optical Coherent Transient Effects in Rydberg Atoms--Dr. W. H. Wing and Dr. R. L. Shoemaker

2-6. Quantum Studies--Dr. M. O. Scully

2-7. Measurement of Fast Relaxation Times in Semiconductors--Dr. M. Sargent

2-8. Infrared Reflectance Spectroscopy of Localized Centers in Silicon--Dr. S. O. Sari

THEORETICAL STUDIES OF THE FREE-ELECTRON LASER

(M. O. Scully)

Funding for this task was assumed by a sponsoring agency.

MOLECULAR INTERACTIONS

(R. L. Shoemaker)

Research Objective: To explore and develop new laser techniques for studying interactions between molecules (i.e., intermolecular potentials) and between a molecule and radiation fields. Particular emphasis will be placed on coherent transient methods that can yield detailed information capable of testing and refining current theoretical models for these interactions.

Progress: Work on the molecular interactions project has been primarily devoted to the development of a frequency switched CO_2 laser system that allows us to observe coherent transient effects in nonpolar molecules. To do frequency switching one places inside the laser cavity an electro-optic crystal whose index of refraction changes when a voltage pulse is applied across it. This changes the optical path length within the laser cavity and hence switches the laser output frequency to a new value.

Difficulties arise because of the properties of the CdTe electro-optic crystal that must be used for frequency switching at 10 μm. In particular, the crystal has very low mechanical strength (approximately like that of chalk), is opaque in the visible, exhibits strong thermal lensing effects, and is piezoelectric--a factor that produces mechanical vibrations when the crystal is excited by an electrical pulse. The mechanical strength and heating problems can be solved by supporting the crystal gently on all four sides using materials that have been machined flat to about 0.0001 in. or better for good thermal contact and minimum mechanical strain. Two of these pieces are made from BeO that has holes drilled in it for direct water cooling; this appears to eliminate the thermal lensing problem, for the laser power levels we are currently using. The fact that the crystal is opaque also means that alignment is difficult, requiring the construction of a special mount with 5 degrees of freedom and the development of new alignment techniques. The most difficult problem is piezoelectric effects that cause the crystal to vibrate when voltage pulses are applied. These must be damped by the crystal mount to avoid large amplitude fluctuations that otherwise occur when the frequency is switched. We have found that these vibrations can be controlled fairly well by using Kovar metal electrodes on two sides of the crystal and a tiny amount of Apiezon T vacuum grease between the crystal and the two BeO insulating pieces. With this combination, we obtain up to 18 MHz frequency switching with only small low frequency variations (<2%).

To take full advantage of the performance of this device, we have also built a computer-controlled data acquisition system to work with it. The system uses a Z-80 microcomputer that controls the frequency switch pulse generator and a boxcar integrator. Scans of up to 4096 points with 12-bit resolution are obtained from the boxcar output and stored in memory where they can be manipulated to do signal averaging, background subtraction, smoothing, etc. A laser stabilization system keeps the CO_2 laser locked to line center, and power variations are corrected by using a power monitor connected to the second input channel of the boxcar integrator.

SF_6 was selected for our initial experiments because it has been studied several times in the past, and there is a long-standing disagreement over the value of T_2 in this molecule. We have obtained very clean photon decay data for SF_6, and find T_2 in reasonable agreement with the original results of Patel et al. [Phys. Rev. 179, 294 (1969)]. However, we also find that the echo decay is nonexponential at short delay times. The data are reminiscent of the behavior caused by velocity changing collisions in CH_3F and NH_2D. The observation of such collisions is unexpected since there are theoretical arguments [C. V. Heer, Phys. Lett. A49, 213 (1974)] indicating that they should not be observed in nonpolar molecules. Since other explanations of the nonexponential decay are also possible, we are presently doing more experiments to try and determine the true origin of the decay behavior. These experiments will be continued under an NSF grant which began this past summer.

Another part of the research done under this contract was the completion of work on a new effect we have named "modulate coherent Raman beats." It is a generalization of the phenomenon of coherent Raman beats, which is the name given to the heterodyne beat observed in the following experiment: One has a three-level system that initially possesses two degenerate upper levels and a single lower level. This system is resonantly excited by a laser of frequency ω_L so that a coherent superposition of all three states is formed. One then suddenly removes the degeneracy and splits the upper levels by applying a Stark field. The laser is left on, and, as a result, two photon transitions occur in which molecules are transferred from one upper level to another by absorbing a laser photon and emitting a photon at $\omega_L + \omega_{12}$ or $\omega_L - \omega_{12}$ where ω_{12} is the splitting between the two upper levels. Since we monitor the total field transmitted in the forward direction, we observe a heterodyne beat between the laser and the fields emitted at $\omega_L \pm \omega_{12}$.

We generalized this experiment by observing coherent Raman beats in a three-level system having two upper levels that are not degenerate but simply closely spaced. When this was done, we observed new strong signals not seen previously. For strong laser fields and Stark shifts on the order of half the upper state splitting, we found that the amplitude of the Raman beat is modulated at a frequency related to an optical nutation frequency. We were able to reproduce these effects quantitatively on the computer shortly after obtaining the experimental results. However, this result alone is somewhat unsatisfactory since it provides very little physical insight into the processes that are occurring. Hence, we also developed an approximate analytic model which shows that the single photon process of optical nutation modulates the two photon transitions that produce the Raman beat by periodically varying the probability amplitudes of the three levels. From our Raman beat data we were also able to determine the electric dipole moment of $N^{15}H_3$ in the $\nu_2 = 1$ state to be μ - 1.286 ± 0.010 Debye, and to measure the Raman beat decay rate, obtaining Γ_R = 63 ± 6 MHz/Torr. Since Γ_R is identical to the excited state population decay rate that we measure using delayed nutation, we can conclude that phase changing collisions are not important in this transition. This work has been written up and accepted for publication in Physical Review A (scheduled for October 1979).

An invited book chapter entitled "Coherent Transient Effects in Optical Spectroscopy" was also completed during the contract period, and will appear in Vol. 30 of the series Annual Review of Physical Chemistry. This chapter reviews recent developments in the field of coherent transient spectroscopy, and also provides, for the first time, a complete bibliography of the literature in the field.

RADIOMETRY OF PARTIALLY COHERENT LIGHT

(A. S. Marathay)

Research Objective: To gain a deeper understanding of the radiometry of partially coherent light so as to be able to solve new measurement problems associated with the use of highly coherent laser sources.

Progress: Attached is a copy of a paper on beam spread calculation. The calculation was done analytically for the ideal case where the source aperture is very large compared to the Gaussian optical intensity profile. In this situation the standard deviation of the Gaussian profile determines the effective source size. The procedure is useful for the case of the laser and the quasihomogeneous source.

For more general cases a computer calculation is called for. In particular we wish to study how the beam energy spreads when the coherence function is of the form

$$\frac{\sin kr}{kr} \quad \text{or} \quad \frac{2J_1(kr)}{kr}$$

where r is a radial coordinate in the source aperture. The spatial Fourier transform of the second form is a constant but that of the first is $(1/\cos\theta)$. To examine the beam behavior in these cases, a computer program was prepared in collaboration with M. J. Lahart (Los Alamos Scientific Lab). It is written for the CDC 7600 computer to take advantage of the large memory. It is based on the calculation of the coherence function by convolving the coherent diffraction pattern with the spatial Fourier transform of the coherence function of the source aperture. Preliminary results have reproduced the results of the analytical calculation with good accuracy. We are now in the process of applying the program for more general coherence functions including those mentioned above.

Physica Scripta. Vol. 19, 40-42, 1979

Directionality of Light Beams and Spatial Coherence

A. S. Marathay and W. P. Goring

Optical Sciences Center, University of Arizona, Tucson, Arizona 85721, U.S.A.

Received September 19, 1978

Abstract

Directionality of light beams and spatial coherence. A. S. Marathay and W. P. Goring (Optical Sciences Center, University of Arizona, Tucson, Arizona 85721, USA).
Physica Scripta (Sweden) 19, 40–42, 1979.

A Gaussian laser source and a quasihomogeneous source (proposed by Carter and Wolf) are compared by studying their respective beam behavior in order to ascertain beam directionality.

In a recent paper [1] Collett and Wolf raised the question: "Is complete spatial coherence necessary for the generation of highly directional light beams?" Following their notation we observe that they consider two sources:

(1) *Gaussian laser source.* For this source the spectral degree of spatial coherence is unity. The Gaussian beam is characterized by the intensity (irradiance) distribution across the source plane by,

$$I_L^{(0)}(r,\omega) = A_L \exp(-r^2/2\sigma_L^2) \tag{1}$$

(2) *Quasihomogeneous source.* This source was first proposed by Carter and Wolf [2]. The degree of spatial coherence is defined as

$$g_Q^{(0)}(r_1-r_2;\omega) = \exp[-(r_1-r_2)^2/8\sigma_L^2] \tag{2}$$

and the optical intensity distribution by

$$I_Q^{(0)}(r;\omega) = \left(\frac{\sigma_L}{\sigma_Q}\right)^2 A_L \exp(-r^2/2\sigma_Q^2) \tag{3}$$

where

$$\sigma_Q \gg 2\sigma_L \tag{4}$$

it turns out that the radiant intensity, $J_\omega(s)$, (see their eq. (1)) function is identical for the two sources (in this calculation the diffraction effects due to the finite size of the aperture are ignored). For this reason they conclude that the beam generated by the quasihomogeneous source is just as directional as a laser beam of much smaller size, say one-tenth the diameter.

It is clear that far enough from the source the propagated beams approach asymptotic limits and in that sense possess unambiguous angular distributions. While this is true far from the source, it is also true that the beams have different behavior close to the source. For this reason we wish to examine the near field behavior of these two source types and study their directionality.

The details of this calculation will be published elsewhere. We make the same assumption made by Collett and Wolf; namely that the physical aperture of the source is very large compared to the width of the relevant Gaussian functions. In this approximation the integrals over the Gaussian functions are taken to extend to infinity across the source plane. The Gaussian irradiance distribution gives an effective width to the source. Most of the energy contained in the source is enclosed by a circle whose radius is determined to be that at which the exponential part of the irradiance falls to the value $e^{-\pi} \simeq 0.043$. For the laser and the quasihomogeneous source the respective radii are $(2\pi\sigma_L^2)^{1/2}$ and $(2\pi\sigma_Q^2)^{1/2}$.

Under these conditions, the spectral irradiance, $\hat{\Gamma}(P,P,\nu)$, at linear frequency $\nu = \omega/2\pi$ and at a typical point P in the plane of observation a distance z from the source is Gaussian in both the Fresnel and the Fraunhofer regions.

The results of propagating each spectral component $\hat{\Gamma}(s_1, s_2, \nu)$ in the source plane to a field plane by the generalized Van Cittert-Zernike theorem [3] for the laser yields,

$$\hat{\Gamma}_L(P,P,\nu) = A_L\left(\frac{4k^2\sigma_L^4}{z^2+4k^2\sigma_L^4}\right)\exp\left[-\frac{r_P^2}{2\sigma_L^2}\left(\frac{4k^2\sigma_L^4}{z^2+4k^2\sigma_L^4}\right)\right] \tag{5}$$

and for the quasihomogeneous source yields,

$$\hat{\Gamma}_Q(P,P,\nu) = A_L\left(\frac{\sigma_L}{\sigma_Q}\right)^2\left(\frac{4k^2\sigma_Q^2\sigma_L^2}{z^2+4k^2\sigma_Q^2\sigma_L^2}\right) \times \exp\left[-\frac{r_P^2}{2\sigma_Q^2}\left(\frac{4k^2\sigma_Q^2\sigma_L^2}{z^2+4k^2\sigma_Q^2\sigma_L^2}\right)\right] \tag{6}$$

where $r_P = (x^2+y^2)^{1/2}$ is the radial distance from the z axis of the point P in the plane of observation.

In the case of the laser the exponential part of the spectral irradiance reaches the value $e^{-\pi}$ when the radial distance is

$$r_P = (2\pi\sigma_L^2)^{1/2}\left(\frac{z^2}{4k^2\sigma_L^4}+1\right)^{1/2} \tag{7}$$

Let us scale the radial distance in terms of the width of the source,

$$r_P = q_1(2\pi\sigma_L^2)^{1/2} \tag{8}$$

and the distance z from the source in terms of the far field distance,

$$z = p_1(2k\sigma_L^2) = p_1\left(\frac{4\pi\sigma_L^2}{\lambda}\right) \tag{9}$$

where λ is the wavelength. With the unitless parameters q_1 and p_1, eq. (7) becomes

$$q_1 = (p_1^2+1)^{1/2} \tag{10}$$

This simple relation describes the spread of energy in the half space to the right of the source as the distance z is varied.

Likewise for the quasihomogeneous source the exponential part of the spectral irradiance reaches the value $e^{-\pi}$ when the radial distance is

$$r_P = (2\pi\sigma_Q^2)^{1/2}\left(\frac{z^2}{4k^2\sigma_Q^2\sigma_L^2}+1\right)^{1/2} \tag{11}$$

By scaling the radial distance in terms of the effective width of the source,

$$r_P = q_2(2\pi\sigma_Q^2)^{1/2} \tag{12}$$

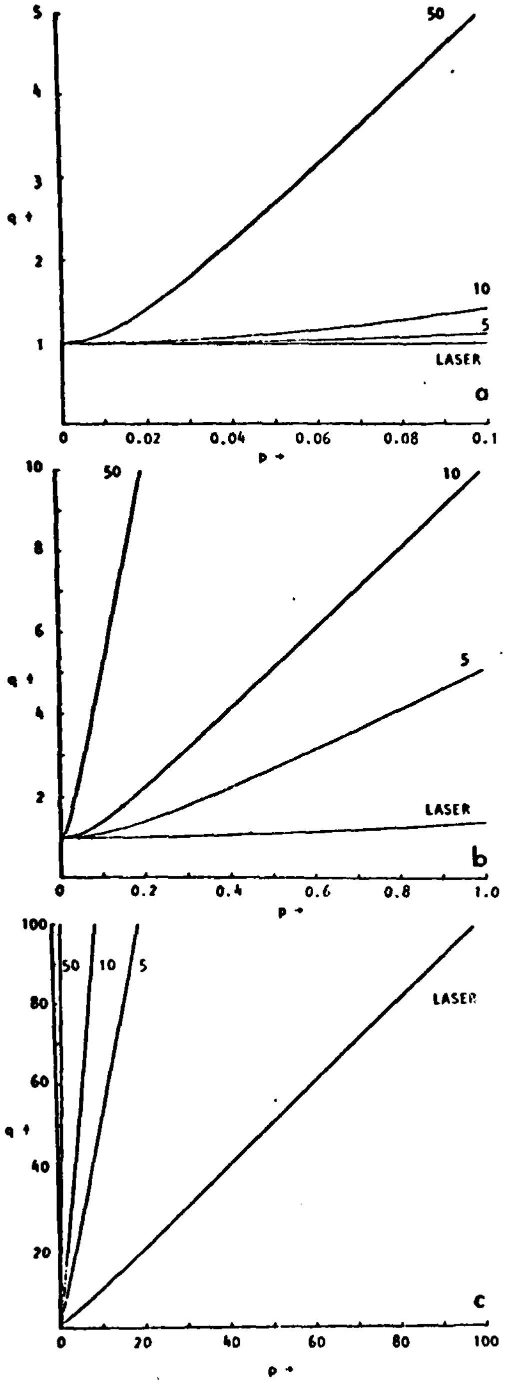

Fig. 1. Plots to show the beam spread as it propagates away from the source. The unitless parameter q is the ratio of the radial distance from the z axis in the plane of observation to the width of the Gaussian irradiance distribution of the source, see eqs. (8) and (12). It is plotted against the unitless parameter p that describes the distance z from the source scaled in terms of the far field distance, see eqs. (9) and (13). The labels 5, 10, and 50 refer to the values of the ratio (σ_Q/σ_L) for the quasihomogeneous source.

and z in terms of what would be a far field distance for the same size coherent source,

$$z = p_2(2k\sigma_Q^2) \tag{13}$$

we find that the unitless parameters q_2 and p_2 fulfill the condition

$$q_2 = \left[\left(\frac{\sigma_Q}{\sigma_L}\right)^2 p_2^2 + 1\right]^{1/2} \tag{14}$$

Here the subscript 2 refers to the quasihomogeneous source. Subscript 1 labels the relevant variables for source 1, namely the laser.

The plots of q vs. p without subscripts are shown in Figs. 1(a), 1(b), and 1(c). In Fig. 1(a) the unitless parameter p varies from the source to one-tenth of the far field distance (well within the Fresnel region). In Fig. 1(b), p varies from zero to unity, which is the limit of the Fresnel region. Finally, in Fig. 1(c), p varies from zero to 100 far field distances, well in the Fraunhofer region; the Fresnel region is barely perceptible on the scale of this graph.

In each graph the curve which obeys eq. (10) is marked, "laser". The other three curves in each figure pertain to the quasihomogeneous source, obeying eq. (14). Curves for values 5, 10, and 50 of the ratio (σ_Q/σ_L) are shown. The graph for the laser case in Fig. 1(c) grows with a slope of 45° as expected in the Fraunhofer region. It is evident from each figure that the light due to a quasihomogeneous source spreads much more than the laser beam as the ratio σ_Q/σ_L is increased. In addition, Figs. 1(a) and 1(b) show that as the ratio (σ_Q/σ_L) is increased, the departure from the laser case occurs nearer to the source location. Of course we should bear in mind that the calculation is in the framework of the scalar theory and as such the ensuing restrictions apply.

It is important to understand that the sole purpose of using the unitless parameters (q, p) is to offer ease of comparison of the distribution of radiation from the two sources placed on an equal footing. That is, given any source, it can be scaled in its own variables. Therefore, it appears that the radiation from a quasihomogeneous source is unable to maintain its directionality in the near field as does the radiation from a laser.

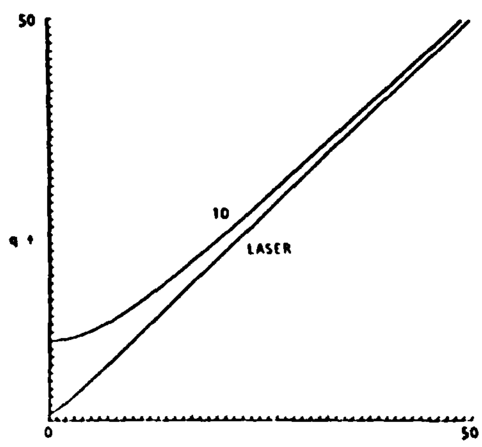

Fig. 2. Plot of a quasihomogeneous source 10 times the aperture size of a laser souce plotted in terms of the laser units. The entire graph is within the Fresnel region of the quasihomogenous source.

Collett and Wolf Calculation

It is pertinent to ask how these results complement the work of Collett and Wolf. They discovered that the radiant intensity is the same for appropriately scaled quasihomogeneous and laser sources. This finding may now be restated as follows. Consider the radiation from a laser whose effective aperture size parameter q is unity, that is, $r_p = (2\pi\sigma_L^2)^{1/2}$ at $z = 0$. For this case the radius of the circle within which most of the energy is contained is plotted in Fig. 2 as a function of the distance z in units of the far field distance as in eq. (9). A similar plot for a quasihomogeneous source whose effective aperture size is 10 times the radius of the laser aperture $\sigma_Q = 10\sigma_L$ (this is their example) is shown in Fig. 2 with the distance z in units of eq. (9). When the variables are scaled in this way, eq. (11) takes the form,

$$q = \left[p^2 + \left(\frac{\sigma_Q}{\sigma_L}\right)^2\right]^{1/2} \tag{15}$$

Thus Fig. 2 clearly shows that for large distances the distribution of radiation due to a quasihomogeneous source becomes similar to that of the laser. In this limit both eqs. (10) and (15) yield $q \simeq p$, or in terms of eqs. (5) and (6) we obtain $\Gamma_L \simeq \Gamma_Q$.

Acknowledgement

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STUDY OF PICOSECOND PROCESSES IN SEMICONDUCTORS

(M. O. Scully)

Publications and Submissions: B. Bosacchi, C. Y. Leung, and M. O. Scully, "Ultrafast processes in the optical response of the electron-hole plasma in germanium," to be published.

PROPOSED EXPERIMENT ON OPTICAL COHERENT

TRANSIENT EFFECTS IN RYDBERG ATOMS

(W. H. Wing and R. L. Shoemaker)

Research Objective: To develop new methods of studying highly excited (Rydberg) states of atoms using the powerful techniques of coherent transient spectroscopy.

Progress: The Rydberg transient project involves an attempt to observe and study coherent transient effects (photon echoes, optical nutation, etc.) and collisional relaxation processes in atomic Rydberg states. Experiments of this sort have never been done before and require a considerable amount of new apparatus. Hence, the construction phase of the experiment has occupied us during the entire contract period. One major task involved the design and construction of the two nitrogen pumped dye lasers required to pump the atoms into the lower Rydberg state. Commercial dye lasers could not meet the specifications we required, so we built dye lasers (a design developed at MIT about two years ago). These provide very narrowband output with exceptional stability due to the fact that no intracavity elements such as etalons or beam expanders are required. Alignment of these lasers was rather difficult and required some modification of our original design in order to do it properly. However, once aligned, the lasers operate very well.

The nitrogen laser pump for the dye lasers is operational, as is the stable CO_2 laser that will include the coherent transients. Thus, work on the various optical sources is essentially complete. The detection system is also near completion except that a channel A divided by channel B output has to be installed on our boxcar integrator.

The other major task involves the sample cell and its supporting equipment. This cell presents a fairly complicated problem since it must simultaneously provide a highly uniform electric field, a clean vacuum, stable elevated temperatures, high resistance to attack by alkali metals, and an optical path and windows for both infrared and visible laser beams. Windows and window seals that meet all these requirements are particularly troublesome. We considered several designs and finally decided on a double window design that uses a pair of hot inner windows to confine the alkali, with vacuum section and cold outer windows outside the alkali cell proper. All the major subassemblies of this cell have been built, including the outer cell envelope, the end plates, the inner hot window mounts, and the Stark plates with their holders and spacers. Some smaller parts remain to be constructed and the various pieces must be integrated into a single working unit. A high vacuum station necessary to handle the alkalis has also been constructed and is operational.

At this point all the major components for the experiments are operational or are in the final stages of construction and assembly. A few pieces of the experiment, such as the beam handling optics and certain aspects of the detection system, remain to be completed. We estimate that we should be able to try the first experiments in about six months.

Work on this experiment will continue under a grant from the Office of Naval Research, which picked up the funding for this project during the past summer.

QUANTUM STUDIES

(M. O. Scully)

Research Objective: Theoretical research related to generation of coherent x radiation, chemical and high energy laser studies, nonequilibrium and coherent transient phenomena in many-body systems, general relativity in quantum optics, and aspects of the foundations of quantum mechanics is proposed.

Progress: In the past six months we have begun a major effort in our program of quantum optics research for JSOP in the field of sensitive ring-laser measurements. In particular, we have been investigating the possibility of using the Sagnac interferometer to detect effects predicted by the general theory of relativity. We have in mind the measurement of "frame dragging" associated with the rotation of the earth. The gravitational field of the rotating earth, described by the Kerr metric, is expected to cause rotation rates based on local inertial measurements to differ from rates based on observation of the distant stars. Preliminary calculations (see attached preprint) indicate that such effects, although small, may be measurable. In addition, we have been continuing our numerical studies of the differential laser gyro (DILAG) to determine its potential for performing accurate rotation rate measurements.

In other work for JSOP we have continued research on coherent transient effects in the Josephson junction and on aspects of the quantum theory of measurement.

Suggestion and Analysis for a New Optical Test of General Relativity

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ABSTRACT

A ring laser interferometer mounted on a rotating platform is analyzed and two experimental tests of general relativity suggested. This apparatus would measure the curvature parameter γ and the drag parameters Δ_1 and Δ_2.

Experiments in general relativity are notoriously difficult. As Misner, Thorne and Wheeler put it in their classic book,[1] "For the first half century of its life, general relativity was a theorist's paradise but an experimentalist's hell." Recently, however, the tools of modern technology in the hands of heroic researchers have led to new tests of general relativity. We here suggest and analyze possible new tests[2] of general relativity using the techniques of precision ring laser interferometry. It is our hope that the present article will stimulate the critical discussions necessary in order to decide the ultimate feasibility of the proposed experiments. Possible applications of such studies to the fields of inertial guidance and geophysics are apparent.

As is well known, light injected into a rotating ring interferometer experiences a differential phase shift between the wave propagating in the same sense (+) or against (-) the direction of rotation.[3] The magnitude of the differential phase, $\Delta\Phi$, between the + and - running waves is given by

$$\Delta\Phi = \int_0^{2\pi} k_\phi^+ d\phi - \int_{2\pi}^{0} k_\phi^- d\phi \tag{1}$$

where $k_\phi^\pm$ is the wave vector for the ± running wave and ϕ is the angular coordinate. For the present purposes it is sufficient to assume that the light travels in a circular path, and is polarized in the $\hat{z}$ direction, perpendicular to the plane of the ring. In such a case the only nonvanishing component of the vector potential is

$$A_3^\pm(\phi,t) = A_0 \exp\left(-i \int k_\mu^\pm dx^\mu\right). \tag{2}$$

Hence, our fields depend only on the temporal ($x^0 = t$) and angular ($x^1 = \phi$) variables. Since we are driving our interferometer by an external signal of fixed frequency $k_0^\pm = \omega$, we need a dispersion relation to determine $k_1^\pm$ in the presence of an arbitrary gravitational field. In order to obtain such a relation we write Maxwell's equations in proper covariant form for the vector potential $A_\sigma(\phi,t)$ in the presence of an arbitrary metric field $g^{\mu\nu}$ as

$$\frac{\partial}{\partial x^\nu} \sqrt{g} \left(g^{\mu\rho} g^{\nu\sigma} - g^{\mu\sigma} g^{\mu\rho}\right) \frac{\partial A_\sigma}{\partial x^\rho} = 0, \quad \mu = 0,1,2,3 \tag{3}$$

where $g = \det g^{\mu\nu}$. The contravariant metric tensor $g^{\mu\nu}$ is, of course, the matrix inverse of the covariant metric tensor $g_{\mu\nu}$ which may be read from the line element appropriate to this problem, namely

$$ds^2 = g_{00} dx^0 dx^0 + 2g_{01} dx^0 dx^1 + g_{11} dx^1 dx^1. \tag{4}$$

Inserting (2) into (3) we obtain the required relation relating $k_\phi^\pm$ to ω:

$$k_\phi^\pm = \left\{ -\frac{g_{01}}{g_{00}} \pm \left[\left(\frac{g_{01}}{g_{00}}\right)^2 - \frac{g_{11}}{g_{00}}\right]^{\frac{1}{2}} \right\} \omega. \tag{5}$$

Then from Eqs. (1) and (5) we obtain the differential phase shift expression

$$\Delta\Phi = -2\omega \int_0^{2\pi} \left(\frac{g_{01}}{g_{00}}\right) d\phi. \tag{6}$$

Likewise, we may operate the ring interferometer by "fixing" the cavity modes $k_1^{\pm} = k$ and measuring the differences between the frequencies $k_0^{\pm} = \omega^{\pm}$. Following a logical development similar to that leading to (6) we find the frequency difference between the two running waves to be given by

$$\Delta\omega = -2kc \int_0^{2\pi} \left(\frac{g_{01}}{g_{00}}\right) d\phi \Big/ \int_0^{2\pi} \left(\frac{-g_{11}}{g_{00}}\right)^{\frac{1}{2}} d\phi \ . \tag{7}$$

The usual Sagnac result may be obtained by transforming the Minkowski line element, appropriate to an inertial frame, to one rotating at a rate Ω. In this case the Sagnac frequency difference is found to be

$$\Delta\omega = \left(\frac{4A}{\lambda\!\!\!^{-} P}\right) \Omega, \tag{8}$$

where A is the area enclosed by the ring interferometer, $\lambda\!\!\!^{-}$ is the reduced wavelength of the injected laser radiation, and P is the perimeter of the ring.

As is clear from Eq. (6), a kind of generalized "Sagnac" effect might be expected whenever we have an off-diagonal metric tensor.[4] In particular recall that the line element for the case of a spherical earth of mass $M_{\oplus}$, radius $r_{\oplus}$ and rotating at a rate $\Omega_{\oplus}$ in "parametrized post-Newtonian (PPN) formalism,[5] is

$$ds^2 = \left(1 - \frac{r_s}{r}\right) c^2 dt^2 - \left(1 + \gamma \frac{r_s}{r}\right) (dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta \, d\phi^2)$$

$$+ 2ac \frac{r_s}{r} \left(\frac{7\Delta_1}{4} + \frac{\Delta_2}{4}\right) d\phi dt, \tag{9}$$

where the Schwarzschild radius $r_s = 2M_{\oplus} G/c^2$ and $a = \frac{2}{5} r_{\oplus}^2 \Omega_{\oplus} \sin^2\theta/c$. The values of the curvature parameter γ and frame dragging parameters Δ_1 and Δ_2, as predicted by various theories, are summarized in the paper by Ni.[6]

Let us now turn to the analysis of an experiment based on the line element (9) which, although *idealized*, contains the essentials of real, and hopefully realizable, tests of general relativity. Consider our ring laser interferometer to be rotating at a rate Ω, a co-latitude θ, and at a distance $\tilde{r} = r \sin\theta$ all relative to the earth's axis. Ultimately we will consider an earth-bound experiment so that $\Omega \to \Omega_{\oplus}$ and $\tilde{r} \to r_{\oplus} \sin\theta$, but added insight is afforded by considering this more general case. Finally the ring laser is allowed to "spin" about its own axis[7] at a rate Ω'. The second rotation, at Ω', is included in the analysis since it will assist us in making precision measurements, as discussed later. Thus we must transform our metric (9) first to a frame rotating about the earth's axis at a rate Ω and then to our platform, which is rotating at a rate Ω'. As the light is constrained to a circular path with radial coordinate ρ in a frame fixed in our rotating platform, we need the metric coefficients $g_{\mu\nu}$ $\mu = 0,1$, where dx^0 and dx^1 now refer to times and angles measured on the platform. The relevant components of the metric tensor in the doubly rotating frame are then given by

$$
\begin{aligned}
g_{00} = {} & c^2\left(1 - \gamma_0{}^2 \frac{r_s}{r}\right) + \gamma(\tilde{r}\Omega)^2 \frac{r_s}{r} + \\
& + 2ac \frac{r_s}{r}\left(\frac{7\Delta_1}{4} + \frac{\Delta_2}{4}\right)\left[\gamma_0{}^2\Omega + \frac{\gamma_0\Omega'}{\tilde{r}^2}(\rho^2 + R\rho\cos\beta)\right] \\
& - \left(1 + \gamma\frac{r_s}{r}\right)\left[\rho^2(\Omega'^2 + 2\gamma_0\Omega'\Omega) + 2\gamma_0\Omega\Omega' R\rho\cos\beta\right]
\end{aligned}
\qquad (10a)
$$

$$
\begin{aligned}
g_{01} = {} & -\left(1 + \gamma\frac{r_s}{r}\right)\left[\rho^2(\Omega' + \gamma_0\Omega) + \gamma_0\Omega R\rho\cos\beta\right] \\
& + ac\gamma_0 \frac{r_s}{r}\left(\frac{7\Delta_1}{4} + \frac{\Delta_2}{4}\right)\left[\rho^2 + R\rho\cos\beta\right]\frac{1}{\tilde{r}^2}
\end{aligned}
\qquad (10b)
$$

$$g_{11} = -\left(1 + \gamma \frac{\tilde{r}_s}{r}\right) \rho^2 \qquad (10c)$$

where $\tilde{r}_s = r_s \sin\theta$, R is the distance from the earth's axis to the center of the ring and $\beta = \phi' + \Omega' t$, where ϕ' denotes an angle measured in the rotating platform. The special relativistic factor γ_0 equals $(1 - (R\Omega/c)^2)^{-\frac{1}{2}}$.

Inserting Eqs. (10,a,b,c) into (7), assuming $R \gg \rho$ and neglecting terms smaller than $\frac{r_s}{r_o} \Omega_\oplus$ we obtain the frequency differential for the present problem

$$\Delta\omega = \kappa \left[\Omega + \Omega' - \tfrac{1}{2}(\gamma+1) \frac{r_s}{r_o} \Omega \sin^2\theta_o \right.$$

$$\left. - \frac{2}{5} \frac{r_s r_\oplus^2}{r_o^3} \left(1 - \frac{3}{2}\sin^2\theta_o\right)\left(\frac{7\Delta_1}{4} + \frac{\Delta_2}{4}\right) \Omega_\oplus \right] \qquad (11)$$

where κ is a constant scale factor and r_o and θ_o are radial and angular coordinates to the center of the ring. The various terms in this expression arise from and reflect the following physical processes: The first two terms, $\Omega + \Omega'$ obviously result from the double rotation of our ring laser. The next two terms arise from the fact that these rotations take place in space curved by a source whose strength is proportional to r_s. Finally the term proportional to $\Omega_\oplus$ is a result of gravitational drag due to the earth's rotation. This dipolar "drag term" falls off as $1/r^3$ which is to be compared with the $1/r$ dependence of the other two general relativistic corrections.

In what follows we will restrict our attention to earthbound experiments so that $r_o = r_\oplus$ and $\Omega = \Omega_\oplus$ in (11). The result (11) has been derived with explicate experiments in mind to which we now turn.

Consider first an experiment in which we rotate our turntable at the modest rate of $\Omega' \sim 1$ Hz, then keeping leading terms in (11) we have the frequency difference

$$\Delta\omega = \frac{\Delta\omega_o}{\Omega_\oplus}\left[\Omega_\oplus + \Omega' + \tfrac{1}{2}(\gamma+1)\frac{r_s}{r_o}\Omega' \sin^2\theta_o\right], \tag{12}$$

where $\Delta\omega_o$ is the frequency splitting when $\Omega' = 0$.

The third term in square brackets is of order $10^{-5}\ \Omega_\oplus$. As discussed later, it should be possible to measure[8] and separate the various contributions to $\Delta\omega$ in (12).

The second experiment is "designed" to observe the effects of gravitational drag. In order to avoid worrying about the gyroscopic scale factor, κ, consider the situation wherein we choose Ω' to produce a null $\Delta\omega$. From Eq. (11) we see that this occurs when

$$\Omega' = -\Omega_\oplus + \left[\tfrac{1}{2}(\gamma+1)\sin^2\theta_o + \frac{2}{5}\left(1 - \frac{3}{2}\sin^2\theta_o\right)\left(\frac{7\Delta_1}{4} + \frac{\Delta_2}{4}\right)\right]\frac{r_s}{r_\oplus}\Omega_\oplus \tag{13}$$

Correction terms due to curvature and drag are apparent. Hence if we can measure $\Delta\omega$, Ω' and $\Omega_\oplus$ to a precision corresponding to a part in 10^9 to 10^{10} of the earth rate, we can sort out the "extra rotation" predicted by general relativity. We now consider the precision to which we can measure these three quantities.

The Sagnac frequency difference $\Delta\omega$ can be used to measure rotation rate in two different types of experiments depending on whether the laser is placed inside or outside of the ring cavity. The "locking" problem associated with internally driven ring lasers has been the subject of recent investigations,[9] and these devices can now operate down to a rate of 10^{-5} to 10^{-6} of earth rate using a ring of 1m diameter. Note that ring radii larger than this are difficult to work with as the laser tends to go multi-mode in that case. However, very interesting new developments in passive Sagnac interferometry, in which the laser is removed from the cavity, allow large ring diameters and also avoid the locking problem. The following is a quote from the paper[10] of Ezekiel et al., "With a 10 m by 10 m cavity and a 4 watt stabilized argon laser it should be possible to reach a sensitivity of $10^{-10}\Omega_{\oplus}$."

The rotation rate Ω' can be measured to a high precision by observing the time it takes for the table to turn through 2π. We can measure the time to essentially "arbitrary" precision. The error in this measurement comes from the angular uncertainty associated with the determination that the table has turned through 2π. However, this too can be accomplished to a very high precision by several optical techniques. For example, we can mount a mirror on the turntable and by means of an autocollimator determine that the mirror has returned to its original position to within $\sim 10^{-4}$ sec of arc.[11] This corresponds to an error $\delta\Omega'$ of about $10^{-10}\Omega'$. By mounting several mirrors on the turntable, we could monitor[12] Ω' quasi-continuously.

Earth rate, $\Omega_{\oplus}$, is known to an amazing accuracy from lunar ranging[13] and very long baseline radio astronomy.[14] We are grateful to Dr. Bender for his comments[15] on the earth rate problem and for the following clear statement, "0.1 millisec [accuracy of measurements of earth's period] over 1 day seems realistic or better if there is little high-frequency noise in UT1." This translates into an error in $\Omega_{\oplus}$ of magnitude $\delta\Omega \approx (\delta T/T)\Omega_{\oplus}$, and since $T \lesssim 10^5$ sec this implies an error in the measurement of $\Omega_{\oplus}$ to a part in 10^9 to 10^{10}.

For a discussion of the techniques of radio astronomy applied to $\Omega_{\oplus}$ see the review by Councilman.[14] Table 1 of that paper lists the expected limitation on earth rotation measurements to be $\lesssim 0.001$ sec of arc. This implies an error in earth rate of $\approx (\delta\phi/2\pi)\Omega_{\oplus}$, i.e., again an error of between 10^{-9} and 10^{-10} earth rate.

In conclusion it appears that state of the art technology applied to the experiment of Eq. (12); could provide a measurement of γ to substantial precision. The frame dragging experiment[16] as implied by (13) would require a measurement of $\Omega_\oplus$ to a part in 10^{10}. At present $\Omega_\oplus$ is known to $\sim 10^{-9}$ to 10^{-10} of earth rate. However, in view of recent accomplishments in the measurement of $\Omega_\oplus$ an extension of current technology to a sensitivity $10^{-10}\Omega_\oplus$ seems likely. Clearly such precision measurements will call for imaginative experimentation, but the problem area[17] is potentially rich in both fundamental and applied payoff.

ACKNOWLEDGMENTS

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4. In an interesting paper V. Braginsky, C. Caves, and K. Thorne [Phys. Rev. D 15, 2047 (1977)] have suggested use of a high Q microwave cavity as a device to detect frame dragging. We thank Prof. Thorne for calling this paper to our attention. An essential difference between that paper and the present work is that our ring laser is mounted on a rotating platform. This notion is central to the analysis and proposed experiments.
5. C. Will and K. Nordtvedt, Jr., Astrophys. J. 177, 757 (1972).
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The frame dragging parameters (Δ_1, Δ_2) assume the values (1,1) in general relativity and $[(10 + 7\omega)/(14/7\omega)1]$ in Brans, Dicke, Jordan theory.

7. In this paper, we take the rotation axis of Ω' to be parallel to the earth's axis.

8. Note that this implies we have "calibrated" our instrument so that we "know" $\Delta\omega_0/\Omega_\oplus$ to approximately one part in 10^9.

9. See, for example, M. Scully, V. Sanders, and M. Sargent, Optics Lett. 3, 43 (1978); and R. Cahill and E. Udd, Optics Lett. 4, 93 (1979). Note that we can measure $\Delta\omega$ to a much higher precision than 10^{-6} $\Omega_\oplus$ since the device is rotating at $\Omega' \sim 1$ Hz and such a rotation produces a bias that keeps the ring laser from locking.

10. S. Ezekiel et al., "Laser Inertial Rotation Sensors," SPIE Vol. 157, 69 (1978).

11. R. V. Shack, Optical Sciences Center, private communication, 1979.

12. This may be accomplished in several ways. Moreover, by averaging over many cycles we can dramatically reduce the effects of random noise.

13. P. Bender et al., Science 182, 228 (1973).

14. C. Counselman, Ann. Rev. Astro. Astrophys. 14, 197 (1976).

15. P. Bender, private communication, 1979. A single measurement of $\Delta\omega$ would take approximately 10 minutes and $\Omega_\oplus$ could be monitored in similar intervals.

16. Space limitations require that several technical aspects of the experimental arrangement have been omitted from the present discussion, e.g., motion of the earth around the sun, earth wobble, etc. Inclusion of these, and other details, presents no real problem and will be discussed elsewhere.

17. For another problem in which off-diagonal elements of the metric tensor are important, see the paper on synchronization in noninertial systems by J. Cohen and H. Moses, Phys. Rev. Lett. 39, 1641 (1977). We are grateful to Professor Cohen for calling this work to our attention.

MEASUREMENT OF FAST RELAXATION TIMES IN SEMICONDUCTORS

(M. Sargent)

Research Objective: To extend the theoretical understanding of relaxation processes in semiconductors beyond those that successfully predicted the experimental spectrum of Keilmann. A Boltzmann-equation treatment of carrier decay should be added to allow a more accurate prediction of the experimental spectrum and to provide a better understanding of the subpicosecond relaxation mechanisms involved.

Progress: This report summarizes efforts for two tasks covering three distinct areas: (1) saturation spectroscopy of p-type Ge, (2) instability studies in optical bistability, and (3) effects of signal detuning on phase conjugation. The three areas are related to one another in that they all involve the interaction of strong and weak waves in two-level media.

The study on saturation spectroscopy of Ge has attempted to explain why the simple Sargent theory worked so well in Keilmann's experiments in view of more elaborate predictions by Sargent concerning oscillating saturability. Tentatively the success has been blamed on the uncertainty principle, which tends to wash out the precise energy values of optical phonons.

The optical bistability work has centered on two areas: (1) the role of significant cavity transmission on the Bonifacio-Lugiato multimode instability (work done with Benza, Bonifacio, and Lugiato), and (2) standing-wave optical bistability and instability (Sargent alone). The former effort reveals that the most pronounced instability occurs for the high-Q cavity treatable by a uniform field approximation. The work is now in the hands of the Italian coworkers, who will draft a paper on the subject.

The standing-wave optical bistability work was presented at an informal session of the Fourth International Conference on Laser Spectroscopy, and as an invited paper at the Sixth Vavilov Conference on Nonlinear Optics (abstract attached).

The phase conjugation work (done with T. Fu) generalizes the theory of resonant four-wave phase conjugation in two-level media to allow the signal wave to be *detuned from the pump waves*. The theory predicts a narrow reflection characteristic strongly dependent on the level lifetimes. Abstracts of papers presented to the LASL Conference on Optics and to Optics Letters are attached.

STANDING-WAVE OPTICAL BISTABILITY AND INSTABILITY*

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ABSTRACT

The transmission characteristics of a Fabry-Perot cavity containing a resonant absorber are described analytically and graphically for arbitrarily intense internal fields. The multimode instability considered by Bonifacio and Lugiato for the unidirectional ring laser is treated for the standing-wave cavity. In particular an instability may exist when the medium is located in the ends of the cavity, but not if the medium fills the cavity. The results are explained in terms of induced sidemode gain and spatial hole burning.

*Presented at the Sixth Vavilov Conference on Nonlinear Optics, Novosibirsk, June, 1979.

Submitted to Soviet J. Quantum Electronics

EFFECTS OF SIGNAL DETUNING ON PHASE CONJUGATION

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ABSTRACT

The Abrams-Lind formulation of degenerate four-wave phase conjugation is generalized to treat signal-pump detuning. The theory is an extension of two-wave grating-dip spectroscopy. We find that the reflection pass-band of phase conjugation is limited by the power-broadened bandwidth of the population difference, a width that can be very narrow. Unlike the running wave saturator case, the signal absorption saturated by a standing wave shows no gain. This is due to the presence of appreciable amounts of unsaturated medium between spatial holes. We also generalize the degenerate three-wave mixing coefficients of Heer to include signal-pump detuning.

INFRARED REFLECTANCE SPECTROSCOPY OF LOCALIZED CENTERS IN SILICON (S. O. Sari)

Research Objective: To characterize and study vibrational transitions of oxygen in silicon and the effect of oxide clustering.

Progress: Oscillator strengths of prominent vibrational transitions of oxygen in silicon have been determined as a function of oxygen content in silane-vapor-deposited silicon films. These parameters were previously unknown. We have also found evidence that these line strengths are functions of the local order in the semiconductor lattice around a given localized site. Second, the effect of oxide clustering on the infrared resonance transitions as well as on the indirect absorption threshold of crystalline and disordered silicon has been studied. This latter work gives experimental evidence showing the necessity of including scattering effects due to multiple-phase structure in mixed crystals. In our particular experiment, it would seem more cumbersome to interpret these same observations from a strictly quantum mechanical view. Thus, this work points out an important new approach to study some new features of solids with nonhomogeneous composition.

CATEGORY 3. OPTICAL DEVICES AND TECHNIQUES

3-1. Absolute Distance Measurement--Dr. J. C. Wyant

3-2. Design Study of a High Performance Scanner/Digitizer System--Dr. P. N. Slater

3-3. Visually Integrated Volumetric Image Display (VIVID)--Dr. R. V. Shack

3-4. Polarization Effects of the Turbulent Atmosphere on a Propagated Optical Beam--R. R. Shannon and C. Ceccon

ABSOLUTE DISTANCE MEASUREMENT

(J. C. Wyant)

Research Objective: A multiple wavelength interferometric technique for measuring absolute distances will be demonstrated experimentally.

Progress: We have investigated the use of multiple wavelengths from a dye laser to perform absolute distance measurements interferometrically to micrometer accuracy. Two techniques for measuring absolute distances were investigated. In the first technique an interferometer using a Spectra Physics model 375 dye laser was set up and fringes were counted as the wavelength was changed from λ_1 to λ_2. The measurement error, ∂L, is given by

$$\partial L = \beta_{12} \frac{\lambda_1{}^2 \partial\lambda_2 - \lambda_2{}^2 \partial\lambda_1}{(\lambda_1 - \lambda_2)^2} + \frac{\lambda_1 \lambda_2}{\lambda_1 \quad \lambda_2} \partial\beta_{12}.$$

$\partial\lambda$ is the uncertainty in the wavelength and β_{12} is the fringe order change resulting from changing the wavelength from λ_1 to λ_2. As a typical example, if the wavelength is changed from 584 nm to 625 nm, distances as large as 1 m can be measured to an accuracy of 1 μm if the fringe order is measured correctly to 1/20 fringe and the frequency difference between λ_1 and λ_2 is known correctly to 15 MHz.

A problem in scanning the wavelength and counting fringes is that the optical path may change during the scanning, in which case a large measurement error can result. The second technique, which was investigated theoretically, involves the use of several wavelengths simultaneously and measuring the relative fringe position for the different wavelengths. It can be shown that q, the number of wavelengths required, is given by

$$q = \frac{\log(L/\partial L)}{\log(P/2)} + 1,$$

where L is the length measured, δL is the error in the measurement, and $1/P$ is the accuracy with which a fringe can be measured.

We are continuing to investigate the two distance measuring techniques in more detail. The accuracy of the scanning technique will be improved in two ways. The motion of the scan mirror in the dye laser will be increased by an order of magnitude so the electronic continuous frequency scan can be increased from 3GHz to 30 GHz. Also, a temperature-stabilized Fabry-Perot etalon will be used outside of the dye laser cavity to measure the frequency scan more accurately.

DESIGN STUDY OF A HIGH PERFORMANCE SCANNER/DIGITIZER SYSTEM

(P. N. Slater)

Research Objective: To improve substantially the performance of a commonly available scanner/digitizer system in terms of its optical, mechanical, and electronic control subsystems in order to meet the need for a cost-effective research tool in basic studies of image evaluation and the fabrication of micrometer-size structures.

Progress: The illumination and collection optics of the standard PDS microdensitometer have been completely redesigned to facilitate the conversion of the instrument to a *linear* scanner (i.e., one not significantly influenced by coherence effects). The modified design, when used with the matched objectives provided for the PDS, yields a fourfold increase in the signal-to-noise ratio (SNR) of the scanner. It also increases the luminance of the viewing screen by a factor of 20. In addition to the higher SNR, the modified system exhibits less thermally induced mechanical drift. The initial redesigned system caused an objectionably high level of flare light to be present. A detailed redesign of the light baffling of the system has reduced the flare light level to 0.1% of the clear signal reading.

VISUALLY INTEGRATED VOLUMETRIC IMAGE DISPLAY (VIVID)

(R. V. Shack)

Research Objective: To define, design, fabricate, and test an experimental model of the three-dimensional VIVID system. The result will be an experimental device suitable for applications testing and for research involving the psychophysics of vision.

Progress: A laboratory model of the VIVID system is currrently under development. This system will be computer controlled, using a Hewlett Packard 2115A general-purpose minicomputer, and will be suitable for carrying out a variety of experiments on the psychophysics of vision. Critical optical and mechanical design phases for the system have been completed, along with a major portion of the system fabrication. Final system assembly and initial testing is expected to be carried out in October, 1978.

The laboratory model will have a 40° field of view, and will be capable of displaying a computer-generated image consisting of a network of up to 30 lines. The image will appear as a real, tridimensional figure suspended in space. The system will require no optical components between the observer and the image.

POLARIZATION EFFECTS OF THE TURBULENT ATMOSPHERE OF A PROPAGATED OPTICAL BEAM

(R. R. Shannon and C. Ceccon)

Research Objective: To determine the extent to which the turbulent atmosphere will modify the polarization state of a propagated optical beam. In addition, if measurable perturbations are detected, to characterize their temporal spectrum as well as the physical mechanism involved.

Progress: An attempt at measuring turbulence-induced polarization fluctuations over a path of approximately 400 m was unsuccessful due to excessive source noise. The noise had large, low-frequency components in the pass-band of the two polarization channels that reduced the sensitivity by at least two orders of magnitude.

A major effort was undertaken to rebuild the laser controller and reduce the noise of the transmitter system. The control problem is complicated by the fact that the light control diode circuit of the Spectra-Physics laser floats at 250 V. This makes modification and improvement of the control circuit difficult. This effort has been successful and a new effort at making atmospheric measurements has been started.

This experiment has impact in several areas. Communication by optical methods through the atmosphere utilizing polarization as the modulation technique could be degraded if the atmospheric turbulence provides state mixing of sufficient level to lower the signal-to-noise ratio. As a by-product, the experimental equipment incorporates a wide bandwidth polarimeter that could possibly be used for high-speed surface ellipsometry measurements such as those performed in the semiconductor manufacturing area.

CATEGORY 4. OPTICAL MATERIALS

4-1. Investigation of Electroreflectance Spectra of Materials Pertinent to the Detection and Generation of Infrared Light--Dr. B. O. Seraphin

4-2. Optical and Mechanical Properties of Doped Copper--Dr. A. B. Meinel

4-3. Dimensional Stability of Doped Polycrustalline Alkali Halide Windows--Dr. S. F. Jacobs

4-4. Investigation of Light Scattering from Mirror Surfaces--Dr. R. V. Shack and D. Thomas

4-5. Study of the Temperature Coefficient of the Emittance of Materials--Dr. B. O. Seraphin

INVESTIGATION OF ELECTROREFLECTANCE SPECTRA OF MATERIALS PERTINENT TO THE DETECTION AND GENERATION OF INFRARED LIGHT

(B. O. Seraphin)

Research Objective: Electroreflectance spectra of materials of the type $Pb_xSn_{1-x}Te$ and $Pb_xSn_{1-x}Se$ will be studied as a function of fractional composition x, doping level, and temperature. These spectra will then be interpreted in terms of the electronic structure and guidelines derived for an optimum technological use of these materials in detection and generation of infrared light.

Progress: During the first 10 weeks of this work, the effort was concentrated on the existing modulation spectrometer. The apparatus, which had been used previously for thermoreflectance spectroscopy, had to be adjusted to operate in the electroreflectance mode. The optical system was realigned and calibrated. The electronic system was adapted to the higher modulation frequency characteristic for electroreflectance.

As a check on the success of this initial phase of adaptation and calibration, the electroreflectance spectrum of germanium was measured. This demonstrates that the setup is ready for the registration of the electroreflectance spectra of the sample set under investigation.

In order to prepare the samples, presently in single-crystalline form, they will have to be cut, polished and etched, and the electroreflectance contact configuration will have to be applied. As a second task during the time period reported here, we have set up a diamond saw and a polisher.

OPTICAL AND MECHANICAL PROPERTIES OF DOPED COPPER

(A. B. Meinel)

Research Objective: We plan to examine the theoretical aspects of the addition of dopants to pure copper and measure the changes in structure and thermal and optical properties of samples based both on our experience with Nobelite and examination of theoretical aspects of different atomic group additions.

PROGRESS: This study was to determine the optical and thermal properties of copper doped with aluminum and indium. It had been noted that small impurity metals added to copper stabilized the copper against loss of reflectance and improved its machining properties. The use of doped copper in diamond-turned mirrors is of practical interest for high-intensity laser applications for three reasons. (1) Good machining properties are needed to get a low-scattering final diamond cut, (2) hardness is desirable if any optical touch-up is done to lower the residual scattering, and (3) high reflectance in the infrared and stability against corrosion and oxidation are necessary.

The doping evaluated was 7% Al, 1% In as prepared by the William Rhodes Laboratory, Phoenix, Arizona, where the material is given the trade name "nobelite." The reflectance of this material as polished at the Optical Sciences Center is shown in Fig. 1. It has significantly higher reflectance than typical Cu + Al alloys in the 0.6 to 3.0 μm region, and follows the curve for gold rather closely, lying about 1% lower in the infrared. Further tests were to be made to better determine the exact value of the high infrared reflectance, but the mirror disappeared.

A new sample is being prepared and will be vacuum melted in the Dept. of Metallurgy laboratories. It is believed that the new sample may have

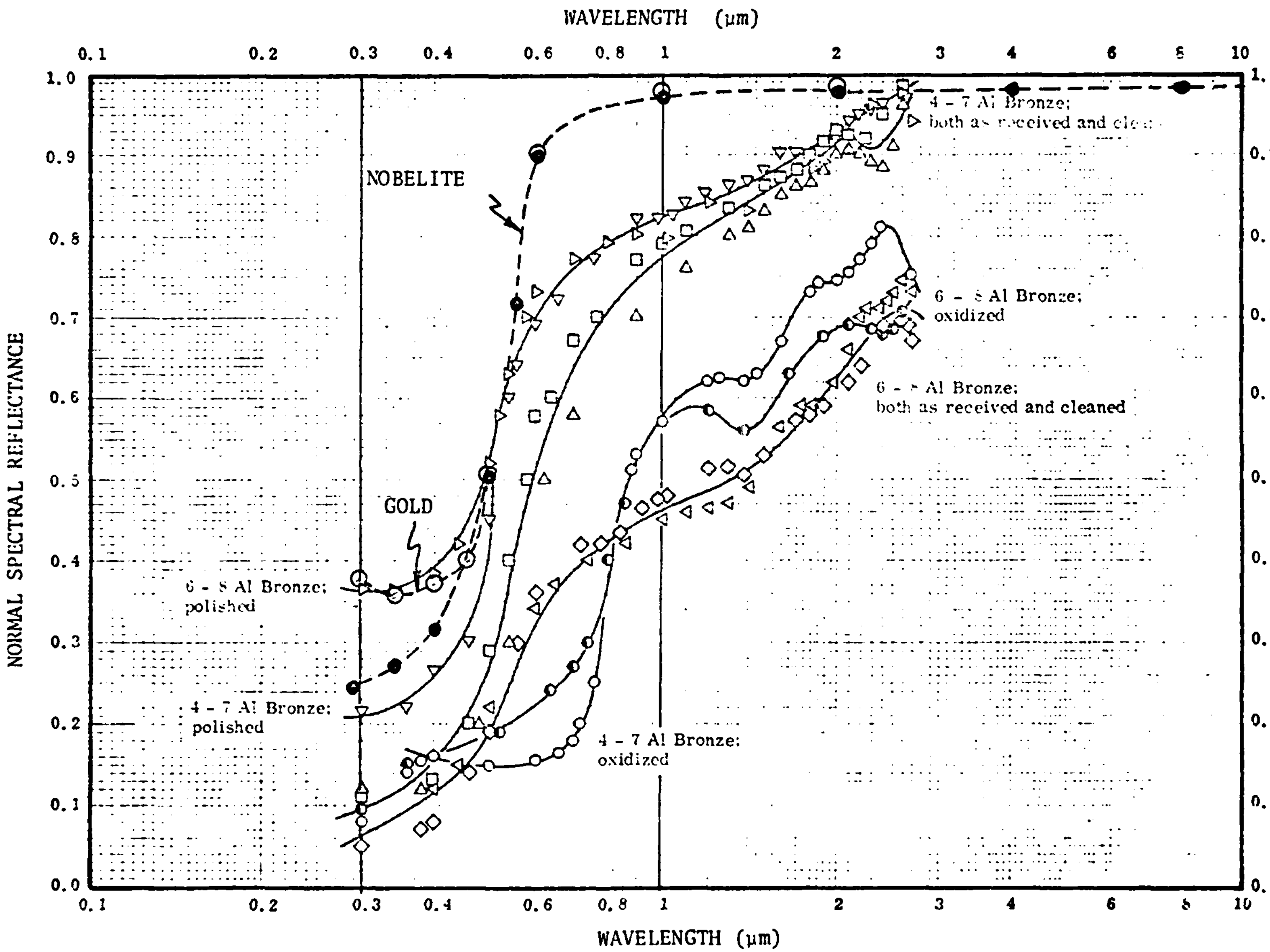

Fig. 1. Spectral reflectance of doped copper.

better reflectance and thermal conductance than the original air-melted batch, which was microporous.

Thermal conductance of copper alloys exhibits anomalous behavior, dropping sharply with even 1% impurity atoms. If nobelite were to follow this trend, it would be as indicated in Fig. 2. This drop of 80% in thermal conductance would be a serious drawback to potential uses of the nobelite copper, but measurements are required in view of the fact that its optical reflectance is higher than for bulk copper alloys.

The new sample will be polished for reflectance and stored for subsequent aging measurements. The sample will also be measured to evaluate the role of vacuum processing on thermal conductance.

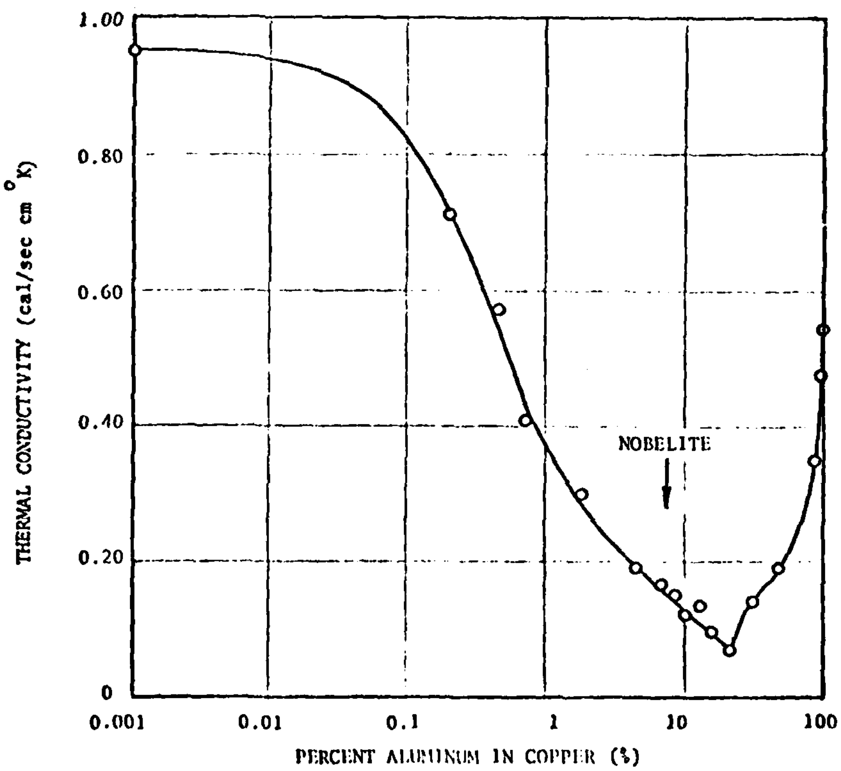

Fig. 2. Thermal conductivity of nobelite.

DIMENSIONAL STABILITY OF DOPED POLYCRYSTALLINE ALKALI HALIDE WINDOWS (S. J. Jacobs)

Research Objective: To measure the bulk dimensional changes with time of new materials which are of interest for high-power laser windows and to investigate the time and temperature stability of low expansion laser structural materials such as Invar.

Progress: Fabrication of the optical samples has been completed. These elements have been sent to China Lake to have the end plates silver coated. We are currently awaiting return shipment from China Lake. Some changes have been made in the vacuum system to improve performance.

INVESTIGATION OF LIGHT SCATTERING FROM MIRROR SURFACES

(R. V. Shack and D. Thomas)

Research Objective: Recent evidence indicates that the measured light scatter from polished surfaces has been predominantly from scattering by particulate matter on the surfaces of the mirrors, rather than from the residual surface roughness. We propose to extend the investigations we have made to include both theoretical and experimental studies of these mechanisms, with at least one goal being the development of a technique to distinguish their separate contributions for a given sample.

Progress: The equipment used for making BRDF measurements has been upgraded to permit the control of the polarization azimuth of the linearly polarized beam that is used to illuminate the samples. The modifications involved the purchase of several optical components and the design and manufacture of suitable mounts for these components. Two major problems have also been encountered with the operation of the experimental apparatus. The lock-in amplifier was found to have a random drift in its output after the manufacturer's prescribed warm-up time for the instrument, and the output power level of the laser source for the equipment has developed an annoying random fluctuation of several percent over time intervals of roughly one second. Both problems prevent proper calibration and alignment of the instrument and would make repeatable scattering measurements impossible. The first has been resolved and the second is currently being investigated.

STUDY OF THE TEMPERATURE COEFFICIENT OF THE EMITTANCE OF MATERIALS (B. O. Seraphin)

Research Objective: To study the temperature dependence of the spectral emittance of materials in the form of thin films and to determine the influence of trace perturbations such as impurities of structural modifications on the sign inversion of the temperature coefficient of the emittance--the so-called z point--with respect to its spectral location. To develop guidelines for the design of improved optical materials by variation of their composition and/or structural habitat.

Progress: The high temperature reflectometer was designed and built by several members of the Solar Energy Group from around 1971 through 1975. Since that time, no major changes have been made. In order to make complete measurements of the optical properties of thin films at high temperature, transmittance, as well as reflectance, must be measured. Such information will guide the development of reflective thin films for high power laser mirrors. We are presently modifying the high temperature cell to accomplish this end.